# Eye Safety and Wireless Optical Networks (WONs)

Jim Alwan, Ph.D.
Manager, Electro-optics Group
AirFiber, Inc.

## Introduction

Wireless Optical Networks (WONs) are beginning to emerge in the telecommunications market as a strategy to meet last-mile demand, enabling reliable high-bandwidth connectivity previously available only to customers directly connected to fiber. Open-air or free-space beams used by WONs to transmit data are not a new concept; historically, such free-space systems were used in point-to-point connections in some campus settings and by the military and the aerospace industry. Expanding into the commercial sector, this technology has evolved into systems with backup and redundant optical links, providing high reliability and fiber-like bandwidth to customers located up to a kilometer away from buried fiber. Such systems are being deployed to commercial buildings in urban areas, breaking the so-called "last-mile" bottleneck. These WONs provide a unique solution that provides higher bandwidth than Radio Frequency (RF) wireless systems and is considerably less expensive than laying additional fiber. Additionally, there are no complex licensing requirements when implementing WONs.

The use of wireless optical networking technology enables carriers to offer low-cost, high-bandwidth services that can be deployed within a short period of time. However, implementing these systems in public spaces provides new safety challenges. Understanding existing eye safety standards, as well as the factors in the WON environment that impact eye safety is essential in addressing these challenges.

Equipment makers, laser safety professionals, and telecommunication service providers are working together to build safe and reliable systems that deliver the next generation of broadband connectivity. This white paper presents a review of laser ocular hazards, present and upcoming safety standards, and eye-safe WON architecture. Additionally, the paper highlights considerations when evaluating the eye-safety of wireless optical networks, and uses the AirFiber OptiMesh Network as an example of a Class 1-compliant WON.

## Light, Lasers, and the Human Eye

The human eye is a sophisticated and sensitive optical detector with a peak visual response to light in the visual range (400–700 nm)[1] that has evolved over time to correspond to the

1. The nanometer (nm) is a unit of measurement used here to describes wavelength. ($10^{-9}$m)

peak of the solar spectrum. Like any other living tissue, the tissues of the eye are susceptible to damage under extreme conditions. Since different tissues absorb some wavelengths more strongly than others, different parts of the eye are variably susceptible to damage at a given wavelength. The cornea (glassy front of the eye), the lens (behind the cornea and in front of the retina), and the retina (the back surface of the eyeball that detects light) are all in the path of light entering the eye and therefore may be subjected to dangerous light levels.

Many factors combine to result in the potential for laser-induced ocular injury. The anatomy of the eye, physiology of vision, and laser-tissue interaction are important factors. Laser-tissue interaction is strongly dependent on wavelength, power, and pulse duration. Damage can occur by several mechanisms including photochemical, thermal, and thermo-acoustic. *Photochemical* interactions are those in which an absorption of a photon by a molecule results in a chemical reaction. *Thermal* interactions refer to the deposition of heat to a local area, whereas *thermo-acoustic* refers to transient phenomena where the rapid deposition of heat results in a damaging shock-wave. In terms relative to the human eye, a thermal interaction might result in a slow burn at the irradiated site, whereas the thermo-acoustic interaction could cause additional physical damage beyond the burn site such as detachment of the retina.

As described, specific tissues in the eye interact strongly with different portions of the optical spectrum. The cornea and lens are transparent to the visible wavelengths and near-infrared, as they are intended to focus visible light onto the retina. However, ultraviolet (180–400 nm) and mid-infrared (1400 nm–3 µm)[2] to far-infrared (3 µm–1 mm)[3] exposure to the cornea and lens can cause photokeratitus and cataracts, respectively. *Photokeratitus* (also known as welder's flash or snow blindness) is similar to sunburn on the cornea. This condition, while painful, does not normally result in permanent damage. *Cataracts* refer to the formation of cloudy regions in the otherwise clear lens, compromising vision as they prevent light from reaching the retina. Visible and near-infrared light is of particular hazard to the retina as this is the range of light to which the eye is intended to be sensitive and thus has a high absorption. Hazardous exposure to radiation in this range can result in retinal burn resulting in compromised vision at the damaged site.

Lasers are potentially hazardous as a result of their high brightness (also known as radiance, $W/m^2$ sr). A handheld laser pointer (~630-650 nm and visibly red) is many times brighter than intense lamps or even direct sunlight. Although a lamp or the sun may have a larger total output of light, it is generally spread into a large solid angle. For example, the sun shines in all directions around it and is thus said to be radiating into $4\pi$ steradians (sr) of solid angle. In direct contrast, a laser can produce a beam of light that spreads very little and radiates into a solid angle several thousand times smaller; thus the brightness is several thousand times higher. It is the collimated, beam-like quality of laser output that results in very high irradiance (also known as power density, $W/m^2$), because lasers can be focused to a much smaller spot on the retina than conventional light sources. Figure 1 provides a comparison of the retinal irradiance of a variety of sources.

2. The micron (µm) is a unit of measurement used here to describe wavelength. ($10^{-6}$m)
3. The millimeter (mm) is a unit of measurement used here to describe wavelength. ($10^{-3}$m)

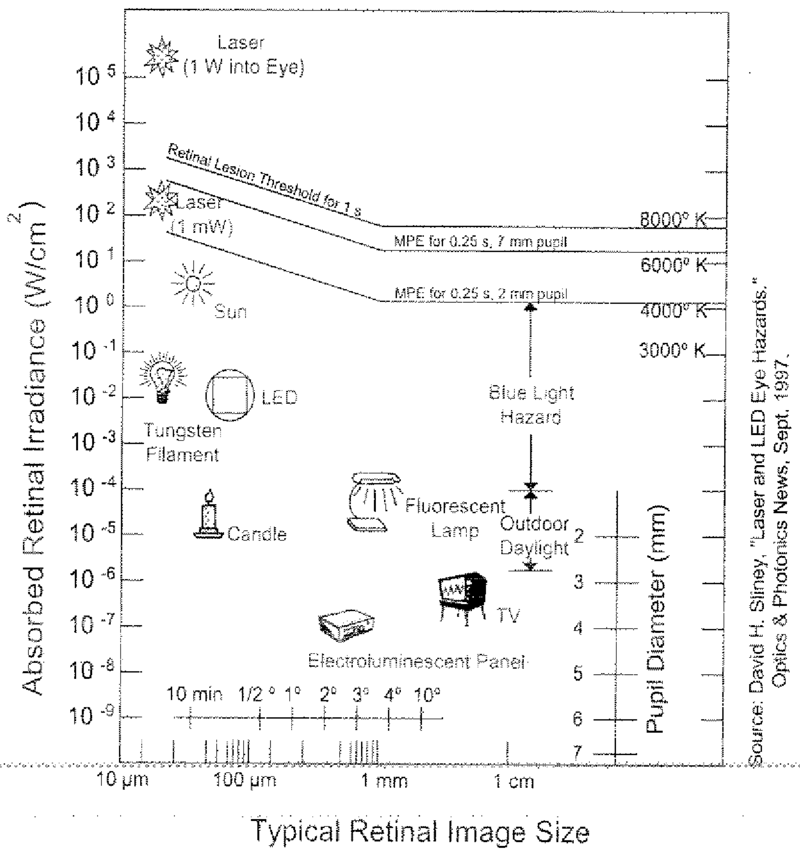


**FIGURE 1. Retinal irradiance for a variety of sources. The retinal image area influences the hazard as does the source radiance.**

## LASER SAFETY STANDARDS

The eye safety hazards of lasers were recognized within a year of the first demonstration of a laser device. As some of the first adopters of laser technology and research, military agencies issued the earliest laser safety guidelines. In the 1960s and '70s, biomedical research regarding laser-tissue interactions established the first physiological basis for safe exposure limits. In over 40 years of research and development, the variety of lasers now spans the spectrum from the vacuum ultraviolet to the far-infrared, with pulsewidths as short as femtoseconds ($10^{-15}$ s). The task of providing laser safety guidelines and regulatory codes that adequately address such a broad field of devices and diverse applications has become significant. Just as the capabilities of laser systems have expanded, so has the complexity of safety standards derived to address them.

There are a number of regulatory, governmental, and educational organizations that have developed and published laser safety standards, three of which are discussed in the following paragraphs. The standards generally have the following main functions:

- Classification of laser systems
- Safety measures for manufacturers
- Guidelines for safe operation by users

Some standards are for manufacturers of laser systems providing regulatory codes on how laser products can be made, classified, and labeled, for example. Other standards are considered user standards and address how individuals and organizations should deploy and safely use laser systems in the community and the workplace.

#### ***ANSI Z136.1 – 1997 THE SAFE USE OF LASERS***

One of the earliest standards that has undergone continual revision since inception in 1973 is American National Standards Institute (ANSI) Z136.1 – 1997 *The Safe Use of Lasers*. This document provides classification based on Maximum Permissible Exposure (MPE) in detailed chart, graph, and equation form, expressing such limits as a function of wavelength and pulsewidth. It is not regulatory but rather a user standard. It has been adopted by corporations, municipalities, and some states in the U.S. as an official standard for safe use and deployment of laser systems. It is aimed at health and safety professionals charged with providing a clear and well-grounded basis for the use of laser systems as they become more prevalent in our everyday life.

#### ***IEC 60825-1 (2000) SAFETY OF LASER PRODUCTS PART 1 - EQUIPMENT CLASSIFICATION, REQUIREMENTS, AND USER GUIDE***

The International Electrotechnical Commission (IEC) IEC 60825-1 (2000) *Safety of Laser Products Part 1 - Equipment Classification, Requirements, and User Guide* is an internationally drafted and recognized technical standard for users and manufacturers. This standard serves as the basis for a subset of standards targeted toward more specific applications; for example, the IEC 60825-2 *Safety of Optical Fibre Communication Systems*. The IEC standards are often directly adopted by countries around the world, or at least form the basis for national policy and regulation on the subject. For manufacturers of products that are sold internationally, compliance with the IEC standards is requisite. In contrast, the United States has an independent standard under the Code of Federal Regulations (CFR).

#### ***21 CFR CH. 1 (4-1-97 EDITION) PART 1040 PERFORMANCE STANDARDS FOR LIGHT-EMITTING PRODUCTS***

The U.S. Food and Drug Administration (FDA) includes the Center for Device and Radiological Health (CDRH), which administrates the US regulatory laser standard. That standard is the 21 CFR Ch. 1 (4-1-97 Edition) Part 1040 *Performance Standards for Light-Emitting Products* Sections 1040.10 and 1040.11. This standard stipulates a classification system, manufacturing and labeling guidelines, and submission of a report of compliance with the CDRH.

Table 1 provides a summary of laser safety standards currently in existence.

TABLE 1.
**Summary of Existing Laser Safety Standards**

| Standard | Type | Target |
|---|---|---|
| ANSI Z136.1 | user | laser users and health and safety professionals |
| IEC 60825-1 | technical | manufacturers with global distribution |
| 21 CFR Ch 1 (4-1/97 Edition) Part 1040 | regulatory | manufacturers in the United States |

# Classification Systems and Certification

**CLASSIFICATION**

There are three concepts that are normally included (directly or by reference) in a laser safety classification system: Class definitions, Accessible Emission Limit (AEL), and Maximum Permissible Exposure (MPE). The class definitions provide non-technical descriptions understandable to the layperson, the AELs define the classification breakpoints, and the MPEs are based on biophysical data and indicate actual tissue damage thresholds.

The classification allows an abbreviated way to readily communicate the hazard level to a user by means of classes 1, 2, 3, and 4, for example. It should be noted that various standards, including those described in the previous section, use confusingly similar yet distinct classifications in the form of Arabic and Roman numerals and upper- and lower-case English letters (e.g. Class 2, II, 2A, 3b). These may appear on a user manual or label, for example. The classes are described in words to indicate the general hazard posed by a laser in a given class. Table 2 shows the classification system of the IEC 60825-1, with the word description and AELs for an example laser of a doubled CW Nd:YAG laser ($\lambda$ = 532 nm). This is a simple example. The addition of pulsed modulation, extended sources, multiple wavelengths and so forth are treated with correction factors. Recently added classifications in the IEC60825-1(2000) include Classes 1M and 2M. These classes take into account that applications exist where aided viewing is not likely. In such cases the AEL is considered for the unaided viewing case only, and therefore Class 1M (2M) is defined as a less stringent class than Class 1(2).

TABLE 2.
**IEC 60825-1 (1998) Classification of Doubled CW Nd: YAG ($\lambda$ = 532 nm)**

| Class | Description | AEL |
|---|---|---|
| 1 | Lasers that are safe under reasonably foreseeable conditions. | 0.39 μW |
| 2 | Visible lasers (400–700 nm) where aversion response such as the blink reflex affords eye protection. | 1 mW |
| 3a | Lasers that are safe for viewing with the unaided eye. Direct viewing of the beam with aids (e.g. binoculars) may be hazardous. | 5 mW |
| 3b | Lasers that are hazardous when the beam is viewed directly. | 500 mW |
| 4 | Lasers capable of producing hazardous diffuse reflections and that may pose skin and fire hazards. | >500 mW |

Note: microwatts (μW, $10^{-6}$W) and milliwatts (mW, $10^{-3}$W) are measurements of power used in the AEL

The AEL refers to the power level at a given wavelength that signifies a laser as belonging to a particular class. Generally, a standard includes tables, graphs, and equations of AELs that allow a person to classify a given laser based on wavelength, power, and pulse duration. The AEL may be related by some safety factor to the MPE values.

The MPE values are based on actual biophysical research of laser-tissue interactions spanning wavelength, power, and pulse duration for a specific tissue. They are defined as the level of laser radiation to which, under normal circumstances, persons may be exposed without suffering adverse effect. The MPE are related to the wavelength, pulse duration, and in the case of visible and infrared, the size of the retinal image. There is a considerable body of research supporting the MPE. As lasers reach new benchmarks of performance particularly in pulsewidth and power, research is performed to estimate the hazard presented. It should be noted that the MPE values are generally derated by a safety factor themselves, adding further margin to MPE-based AELs. In summary, it should be understood that class limits in the form of AELs are not tissue-damage thresholds, but rather are significantly reduced below such limits in the interest of safety.

**Certification**

A Class 1-certified laser is considered eye-safe with no special precautions required for persons who may be exposed to the system. Being Class 1 requires that a system comply with all Class 1 requirements in the applicable standard(s). Most generally this means that the system must limit access to radiation below the Class 1 AEL under any reasonably foreseeable single-fault condition. As previously indicated, AELs for a particular class definition are wavelength-dependent.

The CDRH CFR 1040 and the IEC 60825-1 are self-regulated standards in the sense that the manufacturer has the responsibility to correctly interpret and apply the standards to products. There is no mandatory U.S. Federal or international compliance testing. The perils of not fully understanding and complying with applicable standards are manifold, and include product liability and, most importantly, potential hazard to humans.

There are a number of nationally and internationally recognized, independent laboratories that perform laser product safety testing. Examples include Underwriters Laboratories (UL) and TÜV (Technischer Überwachungs Verein, English translation: Technical Surveillance Organization). The use of an independent test laboratory is good safety practice to ensure that an unbiased party comes to the same conclusion as the people who designed and plan to sell the product. This is particularly important in light of the relative complexity of the laser standards. Most individuals, upon first interpreting the standards, find them difficult to navigate. Employing a laser safety consultant often will save time and money in the development of new laser products, as fundamental design decisions can determine the ultimate laser class of the product and thus the market that the product can address.

## Eye Safety and Wireless Optical Networks (WONs)

With the rapid increase in demand for broadband access and the relative expense and delay in deploying fiber, wireless optical networks are being viewed as an affordable, reliable, and fast method of providing fiber-like bandwidth. Currently, carrier-grade equipment is being built to provide reliable, redundant access networks. Wireless optical technology proposes to break the 'last-mile' barrier -- the relatively short distance between a fiber optic network and a user. In the case of AirFiber's OptiMesh wireless optical network, for example, this is accomplished by Class 1 eye-safe optical transceivers strategically mounted in a mesh configuration on the rooftops of commercial buildings in dense urban areas.

As laser beams become prevalent in public spaces, new challenges arise for manufacturers and users. In response, the IEC is currently drafting a standard under the IEC 60825-1 base standard that specifically addresses open-air communication systems.

## EYE-SAFE SYSTEM ARCHITECTURE

Like many other enabling technologies, potential hazards posed by lasers have been mitigated by the application of safety standards. Lasers are now safely operated in open-air environments as exemplified by the widespread use of laser pointers, laser range-finders, and light shows. Safe operation requires that human access be limited to Class 1 radiation. Evaluating such access for wireless optical networks includes the laser system class, the deployment environment, and beampath. For example, WONs deployed in a space where casual passersby could potentially intercept a beam requires that the system be Class 1 and incapable of delivering radiation in excess of Class 1 (i.e., under single-fault conditions). This may be an unlikely deployment scenario since a WON subject to frequent beam interrupts would not be reliable; however, consider beams being aimed into receivers behind office building windows. The space between the terminals may be virtually inaccessible, but mispointing or beam-spread into adjacent windows must be addressed with reliable systems engineering that meets the standard of safety. Similarly, consider beams being sent and received between tower-mounted rooftop terminals. Although the terminals and space between them may be inaccessible, effective beam-stopping and mispointing again must be addressed and solved with engineering solutions.

There is great diversity in the WON system architectures being developed today. Effecting safe public deployment of these systems requires top-level design choices to limit the access to harmful laser radiation. For example, design features such as the number and size of transmitted beams, divergence, power, wavelength, pulse duration, physical size of terminals, and installation location (i.e., network planning) all must be considered in determining laser system classification and human access. Furthermore, active safety systems that control the laser in response to a potential access event are often implemented. An example is a Location Monitor (LM) system or an Automatic Power Reduction (APR) system.

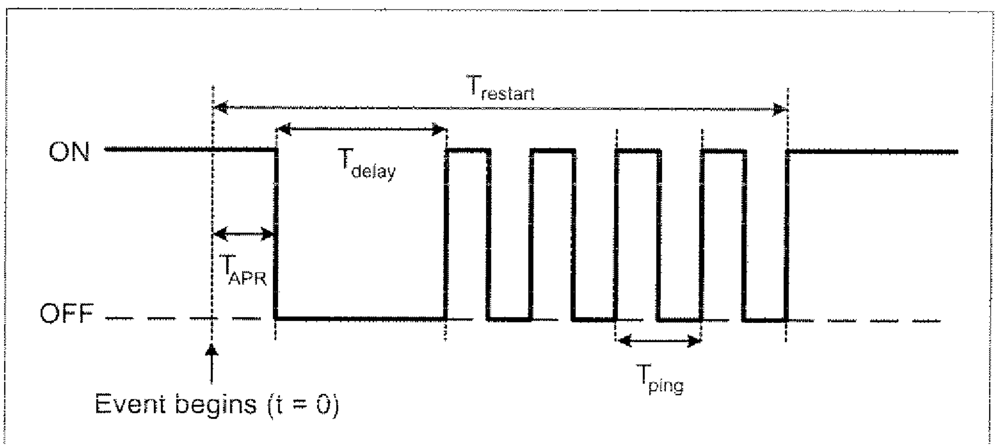


**FIGURE 2.**
**Example Timing Diagram for an APR Response**

An example timing diagram for such an APR is shown in Figure 2, and important time scales are labeled. The constraints on the timing are determined by all the factors discussed above unique to the architecture of WON equipment. The shutdown time of the APR ($T_{APR}$) refers to the time from the instant an exposure event begins to the time the laser is turned off. This response time is determined

such that, under appropriate viewing conditions, a person does not collect greater than the Class 1 AEL in the time $T_{APR}$. If delays can occur in the system, they must be accounted for and included in the safety analysis. An example may include the time between the onset of the event and the time that the system actually senses it. This example includes the use of a 'ping' to test if the link is still blocked. The power of the laser during this pulse and the duration ($T_{ping}$) are chosen such that the Class 1 AEL is not exceeded. It must be assumed that an observer is still intercepting the beam during this time, and the method to test the link must be inherently safe. Depending on the laser power at shutdown time and the power contained in the 'ping,' a delay ($T_{delay}$) may be required to remain eye-safe. Lastly, the total time from the event start ($t = 0$) to the time at which the cleared link is restarted ($T_{restart}$) is similarly chosen so that the system is eye-safe to a viewer who (hypothetically) repeatedly interrupts the beam. A similar Class 1 'ping' could be used for link-acquisition mode, where two transceivers use a stare-scan method to establish the link during installation, for example.

## The AirFiber OptiMesh Class 1 WON

An example of a Class 1-compliant optical wireless system is the AirFiber OptiMesh wireless optical network. The product uses rooftop transceiver nodes that communicate with neighboring nodes. The system uses 785 nm lasers transmitting from a two-inch aperture, and employs an APR system that monitors beam access and reduces output power to Class 1 levels in the event of a beam blockage. (The IEC Class 1 AEL for 785 nm is 0.56 mW.) If a beam interrupt occurs, the APR shuts the system down such that a potential viewer does not collect greater than the Class 1 limit, and traffic is rerouted to a redundant link in the network. The system then enters recovery mode where the link is tested to determine if the obstruction is cleared by use of a Class 1 ping. Once the path is clear, the link is re-established for full data traffic. A redundant system of hardware and software was designed such that the system remains Class 1 under single-fault conditions. Thus, it is a CDRH Class I and IEC Class 1 laser system under applicable standards. Independent certification has been performed by TÜV testing laboratories in which test methods as prescribed by the standards were performed by TÜV representatives, including selectively 'failing' various subsystems to confirm single-fault tolerance.

In summary, top-level performance requirements included laser eye safety in the design and prototype stages to realize Class 1 operation. The installation environment spans restricted or inaccessible space; however, in the interest of public safety, the system was designed to be Class 1. Rigorous testing was necessary to achieve proper operation, and independent testing was performed to confirm compliance.

## Multiple factors impact eye-safety classification

Several other wireless optical systems today use 1550 nm wavelength lasers as an alternative to the shorter wavelengths used by AirFiber. These systems are using lasers and components designed for optimal transmission over optical fiber, since this wavelength is the fiber attenuation minimum. A collateral eye-safety benefit is due to the reduced retinal absorption at 1550 nm compared to shorter wavelengths. For example, the IEC Class 1 AEL for 785 nm is 0.56 mW, whereas the Class 1 AEL for 1550 nm is 10 mW—nearly 20 times higher. Does this mean that 1550 nm systems are 20 times more eye-safe? Not necessarily, as the eye-safety and classification of a WON is a function of many system parameters. There are technology tradeoffs between long and short wavelengths such as detector responsivity and active area. In addition, system performance benchmarks such as designed link length, bandwidth, and availability vary. All of the above determine the amount of laser power required, beam size, and divergence. Thus, to assess the safety hazard of the system, one has to consider the entire system and installation environment.

## Safety Standards for WONs

In response to the growth of free-space optical systems for telecommunications, relevant standards bodies such as the IEC and ANSI are developing standards specifically addressing these systems and the unique laser safety aspects they present. At the time of this printing, these standards are currently under development by the drafting committees within the standards bodies. It may be possible that they are published in final form in the coming year.

The draft standards at present naturally build from related standards addressing optical fiber systems and outdoor laser light shows, for example. Unique features of WONs, such as LM systems and APRs, are also addressed, as are the environments in which they may be operated and the potential for presenting ocular hazards. For instance, systems beaming lasers near street level where passersby may intersect the beam should be rigorously required to be Class 1. On the other hand, systems that send laser beams between towers in restricted environments may be allowed to be in a higher class in recognition of the inaccessibility of the space in which they operate. The committees are composed of laser eye-safety experts, WON manufacturers, optical communication experts, and service providers who will use and deploy such equipment.

## Conclusion

With the upcoming deployment of WONs in the public space, laser eye-safety is an important responsibility of the equipment manufacturers and service providers. Laser light poses unique ocular hazards that must be mitigated by inherently eye-safe system architectures, appropriate installation locations, and equipment reliability. The wavelength, power, and aperture of the laser are important, but the entire system and installation must be considered in determination of the relative safety. Current safety standards address laser eye-safety issues and provide guidance to manufacturers and users. However, unique challenges exist in the deployment of these systems in public spaces and specific standards are being drafted today to address them. The advent of telecommunication-grade WONs and the development of open-air laser safety standards will enable the delivery of fiber-like bandwidth at a fraction of the cost, while ensuring public safety.

A Class 1-compliant wireless optical network exists today in the AirFiber OptiMesh wireless optical network. Class 1 operation was incorporated into the system by design to meet the most rigorous of eye-safety standards while providing reliable, affordable broadband access technology.